BREAKING WAVES, LANGMUIR CIRCULATION AND BUBBLES IN THE MIXED LAYER

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LONG-TERM GOAL

Our goal is to use a combination of measurement and analysis to determine processes responsible for vertical transfer of heat, mass and momentum across the near surface of the ocean. Wave breaking and the role of turbulence and Langmuir circulation in redistributing bubbles are of particular interest.

SCIENTIFIC OBJECTIVES

The key scientific objectives are (i) to test models of turbulence in the upper few metres of the wind driven ocean, especially relating to the effect of wave breaking; (ii) to interpret MBL data showing thermal inhibition of Langmuir circulation;(iii) to determine the response of Langmuir circulation to misalignment between wind and waves.

APPROACH

We are using data acquired with a combination of acoustical and temperature sensors during the Marine Boundary Layer experiment. Doppler sonars were used to measure the organization of bubble clouds by Langmuir circulation and to measure the directional wave spectrum; a mechanically profiling thermistor was used to acquire temperature profiles over the upper 1m of the water column. Since the air-sea heat flux was independently measured, we use the high resolution temperature profiles to examine the turbulent diffusion of heat loss away from the surface. Recent doctoral student Johannes Gemmrich is combining these results with acoustic and temperature measurements of effects due to Langmuir circulation for comparison with models incorporating both turbulent diffusion and advection. Doctoral student Vadim Polonichko is using measurements of the orientation of the bubble clouds associated with Langmuir circulation, together with the orientation of the Stokes drift vector derived from the directional wave measurements to study the response of Langmuir circulation when the wind and waves are not in alignment.

WORK COMPLETED

1. Thermal Inhibition: Suppression of Langmuir circulation by near surface thermal stratification and its subsequent breakdown has been examined with acoustical observations of bubble clouds and temperature data acquired during the MBL experiment(April, 1995). We analyze the transition in terms of the Froude number of the Langmuir circulation derived from the measured

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vertical density gradient, the turbulence field inferred from the measured temperature distributions, velocity and spatial structure of the circulation and the Craik-Leibovich torque.

[Inclusion of the wave enhanced near surface turbulence is essential for the reconciliation of the temporal evolution of the circulation, e.g. cell penetration depth and spacing. Our results thus appear generally consistent with an interpretation based on the stability criterion expressing the competition between mixing layer erosion by Langmuir circulation and buoyant resistance. In the first 1.5 h of the storm the pre-existing stratification inhibited generation of Langmuir circulation, despite the strong wave-wind forcing: U_s~0.2 m/s, H_s on the order of 2 m and inferred sub-critical Langmuir number between 0.09 and 0.025. The stratification delayed deep penetration of Langmuir circulation throughout the whole surface layer by approximately 3.5 h. This interpretation agrees with the observed signatures of Langmuir circulation, derived from the acoustical imaging and is also in accord with predictions of Li et al., (1995) and Gnanadesikan, (1996), who suggest that the presence of pre-existing stratification may delay or inhibit Langmuir circulation.]

2. Langmuir circulation and Wind-Wave misalignment: From acoustical images of the spatial structure of bubbles organised by Langmuir circulation, we have calculated a normalized directivity factor $p(\theta)$, which is an integral measure of the directional energy distribution for all locations in the image. Our approach is to combine these results with acoustic measurements of the directional wave field in order to investigate the response of near surface circulation when wind and waves are not in alignment. A theoretical model has been developed to describe the expected behaviour.

3. Near Surface Turbulence: High resolution temperature profiles acquired over the upper 2m have been compared with an advection-diffusion model where the advection represents available information on Langmuir circulation and turbulent diffusion is estimated from vertical temperature gradients and the known air-sea heat flux.

RESULTS

Directional analysis of bubble cloud images (Figures 1, 2) shows the time evolution of directionality, cell growth rate , wind direction and speed for an experiment in April, 1995. Quite rapid changes in the directionality are successfully interpreted in terms of changes in the relative alignment of the wind and Stokes drift direction. Model analysis predicts generation of the cells distributed over a 20-26° sector, centered between wind and wave directions, consistent with our observations. Our results show that the direction of Langmuir cells depends on the mutual orientation of wind and waves, but is not necessarily aligned with either.

Evolution of the near surface temperature structure at wind speeds >13m/s requires inclusion of a wave enhanced layer of turbulence near the surface. A turbulent length scale of size z_0 ~ 0.2 m has been derived from the temperature profile fine structure (Figure 3, 4). The near surface temperature field shows clear evidence of advective effects due to Langmuir circulation with temperature anomalies O(20 mK) within convergences. These temperature anomalies were observed during the MBL experiment and linked to the occurrence of bubble clouds. From the scale and strength of Langmuir circulation, we extracted the profile of turbulent diffusion from the temperature profiles and used the independently measured air-sea heat flux for comparison with diffusivity profiles obtained from the Craig & Banner (1994) model (Figure 5).

Comparison of the magnitude of vertical temperature fluctuations with a simple model of heat diffusion from a thin surface layer into the water column allowed a further comparison of the Craig & Banner (1994) model with our data. Modeled temperature fluctuations are sensitive to the choice of the empirical constant S_M. We find good agreement with the observed temperature fluctuations for $S_M = 0.39$, the value suggested by Craig & Banner (1994). However, the turbulence closure scheme contains a second empirical constant S_q, which could only be evaluated within the overall performance of the model. Our analysis is based on diffusivity profiles, which are less sensitive to the choice of S_q than dissipation profiles. Modeled dissipation profiles require a surface mixing length of the order of the significant wave height to match observations (Drennan et al., 1996), which is not consistent with our findings.

Analysis of thermal inhibition of Langmuir circulation appear consistent with a stability criterion based expressing the balance between mixing layer deepening due to Langmuir circulation and buoyancy effects. It was observed that near surface stratification had the effect of delaying onset of Langmuir circulation after the beginning of a storm, even in the presence of strong wind wave forcing.

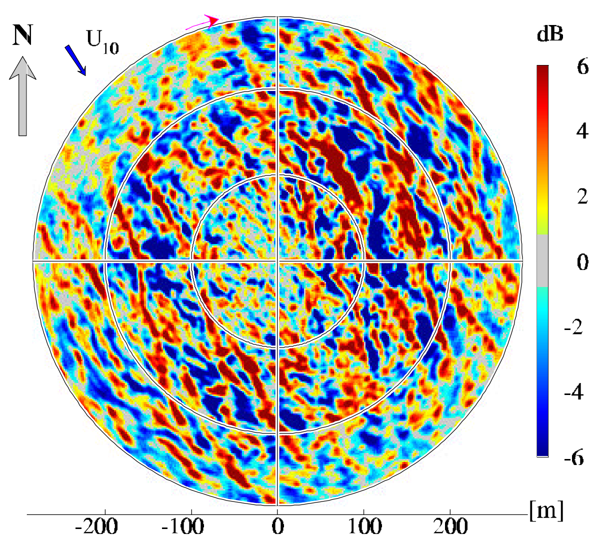

Figure 1: The near surface acoustical backscatter intensity distribution. High backscatter regions (red) are bubble clouds organized by Langmuir circulation.

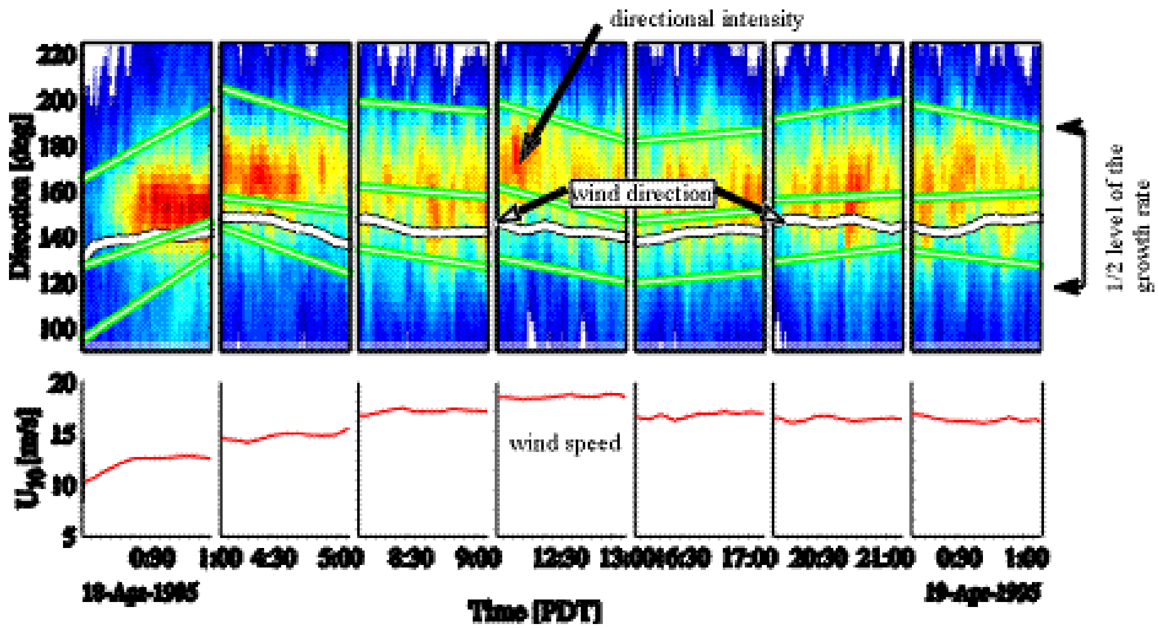

Figure 2 : Normalized directional intensity factor $p(\theta)$, growth rate, wind speed and direction. Three thin lines mark the maximal and half power levels of the circulation growth rate, calculated using modified Craik-Leibovich model and observed from the directional wave field.

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Figure 3: Representative near surface temperature profiles (line) on 18/04/95 at a) 0033h and b) 0448h. Dots give temperatures recorded with fixed depth thermistors. The depth is referenced to the instantaneous surface detected via the capacitance wire gauge.

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Figure 4: Mean values of turbulent length scale, obtained from 1000 bootstrap iterations of vertical extension of temperature disturbances, and a linear fit. Error bars represent one standard deviation.

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Figure 5: Comparison between observations and modeled turbulent diffusivity profiles. Diffusivities are normalized by the diffusivity expected in a constant stress layer $\kappa u_* z$, with von Karman constant κ=0.4 and friction velocity u_*

IMPACT/APPLICATION

The near surface structure and its response to changing wind and wave conditions helps to determine the vertical transport of key oceanographic variables such as heat, mass and momentum. A particular example is the turbulent and advective transport of bubbles, from their creation in breaking waves to their escape to the surface or their loss through dissolution. As well as contributing to the air-sea transport of gas, bubbles have a profound effect on the acoustical environment of the surface layer.   The measurements and analysis summarized here contribute to our understanding of this near surface environment and thus to our ability to model and predict characteristics of the upper ocean boundary layer. For example, models of near surface bubble distributions depend on prescribed conditions of turbulent diffusivity and advection. We have found that an advection-diffusion model can provide a consistent interpretation of observed near surface temperature structure; this can serve as a background environment upon which to model bubble distributions. Some of the results are at variance with expectations, for example the smaller surface roughness scale inferred from our temperature profiles. Such discrepancies motivate further analysis and the design of more complete measurement approaches.

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